Stone temperature and moisture variability under temperate environmental conditions: implications for sandstone weathering

McAllister, D., Warke, P., & McCabe, S. (2016). Stone temperature and moisture variability under temperate environmental conditions: implications for sandstone weathering. DOI: 10.1016/j.geomorph.2016.12.010

Published in:
Geomorphology

Document Version:
Peer reviewed version

Stone temperature and moisture variability under temperate environmental conditions: implications for sandstone weathering

Daniel McAllister[1], Patricia Warke[2]* & Stephen McCabe[3]

[1] The Dow Chemical Company – Belfast, Northern Science Park, Belfast BT3 9DT, United Kingdom,

[2] School of Natural & Built Environment, Queen's University Belfast, Belfast BT7 1NN, United Kingdom

[3] Northern Ireland Environment Link, 89 Loopland Drive Belfast BT6 9DW, United Kingdom

*Corresponding Author: Patricia Warke – p.warke@qub.ac.uk

Abstract

Temperature and moisture conditions are key drivers of stone weathering processes in both natural and built environments. Given their importance in the breakdown of stone, a detailed understanding of their temporal and spatial variability is central to understanding present-day weathering behaviour and for predicting how climate change may influence the nature and rates of future stone decay.

Subsurface temperature and moisture data are reported from quarry fresh Peakmoor Sandstone samples exposed during summer (June–July) and late autumn / early winter (October–December) in a mid-latitude, temperate maritime environment. These data demonstrate that the subsurface thermal response of sandstone comprises numerous short-term (minutes), low magnitude fluctuations superimposed upon larger-scale diurnal heating and cooling cycles with distinct aspect-related differences. The short-term fluctuations create conditions in the outer 5–10 mm of stone that are much more 'energetic' in comparison to the more subdued thermal cycling that occurs deeper within the sandstone samples.

Data show that moisture dynamics are equally complex with a near-surface region (5–10 mm) in which frequent moisture cycling takes place and this, combined with the thermal dynamism exhibited by the same region may have significant implications for the nature and rate of weathering activity. Data indicate that moisture input from rainfall, particularly when it is wind-driven, can travel deep into the stone where it can prolong the time of wetness. This most often occurs during wetter winter months when moisture input is high and evaporative loss is low but can happen at any time during the year when the hydraulic connection between near-surface and deeper regions of the stone is disrupted with subsequent loss of moisture from depth slowing as it becomes reliant on vapour diffusion alone.

These data illustrate the complexity of temperature and moisture conditions in sandstone exposed to the ‘moderate’ conditions of a temperate maritime environment. They highlight differences in thermal and moisture cycling between near-surface (5–10 mm) and deeper regions within the stone and contribute towards a better understanding of the development of structural and mineralogical heterogeneity between the stone surface and substrate.

Keywords: Peakmoor sandstone; temperature; moisture; weathering

1.0 INTRODUCTION

Temperature and moisture are key drivers of sandstone weathering processes in both natural and built environments. The temperature of stone is a major factor in determining the rate and direction of energy and moisture transfer and its exchanges with the atmosphere (c.f. Hillel 1998). Temperature also governs the nature and intensity of the chemical, physical and biological weathering processes that contribute to the decay and modification of sandstone by controlling the rates and frequency of their operation. The presence of moisture is central to the effective operation of the majority of mechanisms driving stone decay and understanding its mobility within stone and how this varies over space and time is essential.

However, current understanding of stone temperature characteristics under natural conditions of exposure is considerably more developed than that for moisture content principally because temperature is recognised as generally being easier to measure (McGreevy and Whalley 1987; Hall and André 2001). Consequently, it is not surprising that there exists an extensive literature documenting thermal observations of stone and monitoring programmes conducted in a wide array of geographical settings (see Table 1 for examples).

These studies have had a tendency to highlight temperature maxima/minima and ‘typical’ diurnal regimes, with more recent studies placing emphasis on spatial and temporal thermal variability at decreasing scales of enquiry (e.g. Gómez-Heras *et al.* 2006; Hall 1997; Hall and André 2001, 2003; Jenkins and Smith 1990; Smith 2009). But, what is of more concern is the fact that many of these geomorphologically focussed observations have largely concentrated on thermal conditions experienced in the more ‘extreme’ climatic locations such as hot and cold deserts and high altitude environments – typically driven by the ongoing debate over the role of insolation weathering in the breakdown of stone (McFadden *et al*, 2005).

Although such observations have undoubtedly helped to shape the design of laboratory weathering simulation experiments, it is important to remember that arguably, they represent the extreme ends of the climatic spectrum. Consequently, more may be known about stone temperature conditions in 'extreme' environments than more temperate conditions thereby resulting in an understanding based on a rather skewed dataset.

Because the presence of moisture is central to the effective operation of the majority of mechanisms initiating and driving stone breakdown, understanding its dwell time and mobility within stone is essential. However, much of our current understanding is based on assumption rather than empirical evidence primarily because of the difficulty of collecting accurate data over meaningful time periods especially in field-based settings. The key problems associated with measuring subsurface moisture content of stone using technologies such as capacitance humidity sensors, resistivity probes and electrical resistivity tomography, is a low level of sensitivity to change especially under conditions of saturation, measurements that can be influenced by the ionic content of the moisture and the potential for sensor drift from an initial calibrated state (for examples of use see; Srinivasan *et al*, 2010; Smith *et al*, 2011; McAlister *et al* 2011; Sass and Viles 2010a and 2010b; Sass 2003; Stojanovič *et al,* 2010). In addition, the very act of drilling into stone for positioning of moisture sensors can create conduits for preferential moisture flow and accumulation. Although, in comparison to the collection of thermal data, the collection of reliable stone moisture data remains challenging, in recent years the situation has started to improve with technological developments in moisture measurement associated with research being undertaken in the soil and medical sciences (Hall 2007; Sass 2005; Pel and Huinink 2009).

Temperature and moisture conditions within stone are closely interconnected, with change in one resulting in alteration of the other. Their role in stone weathering is pivotal but the extent and potential complexity of their temporal and spatial variability in temperate environments is not fully recognised and hence not fully understood. This study, and the data reported, seeks to redress this situation with an investigative focus on the following two areas:

1. Identifying temperature characteristics of sandstone samples exposed in a temperate, mid-latitude environment with the aim of clarifying the nature and extent of stone temperature variability with depth and over time.
2. Identification of the spatial and temporal variability of moisture content in sandstone in response to changing meteorological conditions.

These data provide the basis for questions about the potential effectiveness of weathering processes in temperate environments and the complexity of thermal and moisture response characteristics in the outer few millimetres of stone and conditions in deeper substrate regions.

2.0 MATERIALS AND METHODS

Temperature and moisture data were collected from Peakmoor Sandstone samples in an outdoor test facility in Belfast, Northern Ireland. Detail of the sandstone, the field site and data collection methods is given in the following sections.

2.1 Material Properties

Peakmoor Sandstone is a buff-coloured, quartz-rich, fine to medium grained Millstone Grit of Carboniferous age (350–300 Ma) with a relatively homogenous structure in which, for the most part, obvious bedding and micro-lamination structures are absent. A summary of material properties and pore size distribution as determined by Mercury Intrusion Porosimetry (MIP) are shown in Table 2 and Figure 1, respectively. Mineralogy and porosity properties are important because of their role in determining the thermal properties of stone and its ability to absorb moisture, transfer it to deeper substrate layers and restrict its loss through evaporation.

2.2 Field Site

Northern Ireland is located at approximately 55°N 6°W (Figure 2) and because of this mid-latitude location and its position on the edge of the North Atlantic is subject to temperate maritime climatic conditions where extremes of temperature are rare because of the ameliorating effect of the North Atlantic and the Gulf Stream (Betts 1997). The prevailing direction of incoming weather systems is from the southwest with the flow typically dominated by the passage of low pressure (cyclonic) systems usually of 2–3 days duration interspersed by high pressure (anticyclonic) conditions of varying intensities which, when strongly established can sometimes persist for a week or more.

While the average meteorological values shown in Table 3 mask the extremes that can occur (see McAlister *et al*, 2013), they demonstrate the ‘moderate’ nature of conditions that dominate in this mid-latitude location.

2.3 Experimental Set-up and Data Collection

The test unit assembly was securely sited in the city of Belfast. It was constructed using a galvanised steel frame into which plywood sheets were set with a wooden lid that enclosed the interior where the data-loggers were located (Figure 3).

The 'quarry fresh' Peakmoor sandstone was cut into blocks (200 mm length X 100 mm width X 200 mm depth). Four sides of each block were sealed with a coating of varnish and placed in a 20 mm thick 'jacket' of expanded polystyrene. This was done to insulate the blocks and to limit heat and moisture exchange with the external environment to just the outer exposed face of each block. This method has been used in previous studies (e.g. Smith *et al*, 2008; Smith *et al*, 2011) and has the effect of enabling smaller blocks to mimic the response characteristics of larger pieces of stone. Following preparation, each block was placed into pre-cut slots in the plywood sides of the test unit.

The test structure was orientated to ensure that the blocks faced northeast (NE), southeast (SE), southwest (SW) and northwest (NW) thereby enabling the identification of aspect-related differences in thermal and moisture characteristics (Figure 3).

2.3.1 Monitoring meteorological conditions

A Davis Vantage Pro II weather station was located several meters from the test unit with weather data recorded at one-minute intervals. Simultaneous meteorological data allows meaningful comparison with, and interpretation of, sandstone response to changing external conditions.

2.3.2 Temperature data collection

Collecting stone surface temperature measurements can be problematic as generally the process involves the use of thermistors, thermocouples, micro-electro-mechanical sensors (MEMS) or iButtons in direct contact with the stone. As such, their very presence may alter stone surface temperature through shielding effects such that the recorded temperatures may represent heat conducted from the surrounding material and negate the effect of radiative heating (Warke 2000), or that the recorded temperature may reflect the sensor response to radiation more than that of the stone surface itself. Attempts have been made to address such issues through the use of non-contact infrared devices but although this may be applicable for collection of surface temperature data, the collection of subsurface data is constrained by current technology and can only be done using direct contact methods.

Because of the problems associated with surface temperature recording, on site stone surface temperature was not measured in this study with the emphasis instead on near-surface and deeper thermal response of the sandstone blocks. Consequently, temperature sensors were positioned at depths of 5, 10, 20, 50 and 100 mm from the exposed block surfaces (Figures 4a and 4c). The sensors used at this site were 5 kohm NTC thermistors with a bead diameter of 2.4 mm, a response time of 15 seconds and an accuracy of ±1%.

The sensors were inserted into 6 mm wide pre-drilled holes at the rear of the blocks which were then back-filled with powdered stone and plugged with mastic adhesive (Figure 4b). Data were recorded at intervals of five minutes during the summer months (June and July) and at intervals of one minute during the October to December recording period. This difference in data recording intervals reflects some unavoidable technical issues but the resultant data still provide a robust record of thermal response of the Peakmoor sandstone samples.

2.3.3 Moisture data collection

A variety of direct and indirect stone moisture measurement methods exist and can vary widely in reliability, ease of use and accuracy (Hall and Hoff 2002). Data reported here were collected using custom-made 2-pin resistivity probes. As with the temperature sensors, the moisture measurement probes were inserted into separate pre-drilled holes to depths of 5, 10, 20, 50 and 100 mm from the exposed block surfaces (Figures 4a–c).

Resistivity probes provide an indirect method of moisture measurement that relies on varying dielectric properties of the stone with changing moisture content. The resistivity value or Resistance Ratio (RR) provides a 'measure' of moisture content with decreasing values indicative of wetter conditions and vice versa. This method is particularly useful for monitoring change in conditions over time and offers a relatively high level of precision (e.g. Srinivasan *et al,* 2010; Smith *et al,* 2008, 2011). However, this method is not perfect as sensitivity can decrease under saturated conditions and measurements may be influenced by ionic content of moisture although the latter should be less problematic in this instance because 'quarry fresh' stone was used and therefore free ion content within the samples was minimal.

These methods of moisture and temperature data collection, by their intrusive nature, may provide an approximation of the actual internal conditions of the stone but it is not possible, given current technology, to calculate the effects of the methods of data collection used on the precision of the resultant data. We can infer that the aspect and depth related differences in temperature and moisture results reported in the following sections indicate that the sensors within the stone samples are sufficiently accurate to reflect differences in the receipt of direct insolation and moisture input from directional rainfall and that the near-surface temperatures are in line with the external air temperatures.

3.0 RESULTS AND INTERPRETATION

Temperature and moisture data are reported separately in the following sections but because of the quantity of material collected only selected representative sections of the total dataset are presented.

3.1 Overview of Temperature Data

Internal stone temperatures collected at depths of 5, 10, 20, 50 and 100 mm below block surfaces for June–July and September–December monitoring periods are presented in Figures 5a and 5b, respectively. Because of the quantity of data collected the focus here is on the response of the NE and SW facing test blocks as being representative of the greatest differences in direct input of solar radiation with the SW facing block experiencing the greatest potential for receipt of solar energy while the NE facing block had the least.

The temperature characteristics of each depth from these two aspects are summarised in Tables 4a and 4b for the June–July and September–December monitoring periods, respectively. Despite differences related to aspect, which will be discussed later, the 'pattern' of stone temperature response is broadly similar with temperature conditions reflecting diurnal heating and cooling cycles with the amplitude of these cycles increasing and decreasing in response to the passage of synoptic weather systems.

The difference between daily stone temperature highs and lows varies considerably from around 2°C to 22°C for example, between weeks 5–7 (June–July period). The diurnal temperature difference at 5 mm depth in the SW facing block during summer (Figure 5a) ranged from 2–3°C during a period of low pressure cyclonic conditions with the associated cloud cover; following this, high pressure brought clear sky conditions producing a diurnal temperature range of around 22°C.

The anticyclonic conditions that developed towards the end of July were associated with the recorded subsurface stone temperature maxima (Table 4a). As expected, these values were highest at 5 mm below the block surface, with temperatures of 26.7°C and 34.6°C being experienced in the NE and SW facing blocks, respectively. These stone temperatures exceed the highest air temperature of 23.5°C recorded during the same monitoring period. During the June–July monitoring period stone temperature maxima were lowest at 100 mm depth and stone temperature minima were relatively similar at all depths and across all aspects, ranging from 5.7–6.4°C (Table 4a).

During the September–December recording period, stone temperature maxima (at all depths) were again highest in the SW facing block. Stone temperature maxima at 5 mm depth were 17.0°C and 23.0°C for the NE and SW blocks, respectively; the maximum air temperature recorded was 17.0 °C while the maximum temperatures experienced at 50 and 100 mm depth were slightly lower than this value (Table 4b). During this monitoring period stone temperature minima reached -2.5 °C. The results presented highlight aspect- and depth-related temperature differences.

3.1.1 Aspect-Related Temperature Fluctuations

Figure 6a (Inset 1) shows stone temperature data at 5 mm below the stone surface for a cloudy summer day in July in which stone temperatures present a ‘dampened’ diurnal range relative to the rest of the two-week time series and particularly in comparison to temperature response to ‘clear sky’ conditions (Figure 6b).

Under cloudy conditions aspect-related differences are minimised producing similar thermal responses and a depressed diurnal regime which, on the cloudy day was reduced to 5.5–6.0°C.

Stone temperatures throughout the day exhibit a sinusoidal distribution (c.f. Gómez-Heras *et al.* 2008), which, combined with the consistency between aspects (differing by no more than 0.2°C) suggests the dominance of convective heating throughout the day through the direct transfer of heat energy from the air in contact with block surfaces into the stone. As shown in Figure 6a, low levels of radiation were recorded with a daily maximum of 323 W/m^2.

Figure 6b presents the same variables for a day characterised by ‘clear sky’ conditions when stone temperature conditions were markedly different with a pronounced aspect-related variability evident throughout the day. Air temperatures exhibited a diurnal range of 8.3°C; while stone temperatures at 5 mm depth in the NE and SW facing blocks produced temperatures of 11.5°C and 20.1°C, respectively. The maximum air temperature was 22.2°C whereas stone temperature maxima were 25.7°C and 34.5°C for the NE and SW blocks, respectively. The timing of stone temperature maxima for each aspect and the curves of daily distributions of temperature identify two overlapping heating regimes – convective and radiative heating (with the latter occurring when stones are in direct receipt of solar radiation).

Before sunrise, subsurface stone temperatures were consistent across all aspects decreasing close to the ambient air temperature, reflecting heat flux to the atmosphere and establishment of relative equilibrium between the air temperature and the outer few centimetres of stone (Figure 6b, Inset 2). Following sunrise, at 05:00 hours, temperatures at 5 mm depth in the NE facing block increased rapidly (from 14.4°C to 20.3°C over a one hour period). Meanwhile stone temperatures in the other aspects showed values of between 14.6°C and 15.2°C. During this period the temperature distribution in the NE facing block showed a radiative pattern of heating that coincided with an increase in total solar radiation. At around 11.00 hours the temperature distribution in the NE facing block appeared to change to a sinusoidal pattern that reflected it being thrown into shade as the sun tracked through the sky with convective processes largely controlling heat transfer between air and stone.

Radiative heating was experienced next in the SE, then the SW and finally in the NW facing blocks, reflected again by increasing stone temperatures to values considerably higher than ambient air temperatures. The SW facing block appeared to receive the most irradiance, and was over 10°C warmer than air temperatures recorded at the same time demonstrating the importance of radiative heating processes on stone thermal regimes.

When direct receipt of solar radiation ceases, or is interrupted by, for example, the passage of clouds, such as that shown by the SW facing sample at around 19.00 hours, or by shading related to structural influences (nearby buildings), such as that which occurs around 07.30 hours affecting the NE facing block, stone temperatures experienced an exponential decrease (c.f. Gómez-Heras *et al.* 2008).

Stone temperatures at 5 mm depth and air temperatures are presented for a three-day period in November (Figures 7a and 7b) to illustrate the role of convective and radiative heating regimes. Because of the changing position of the sun in the sky (that is the solar azimuth at times of sunrise and sunset) during winter only the SE and SW aspect experience the overlapping of convective and radiative (through direct insolation) heating regimes. Clear sky conditions persisted throughout the 21st November, as evidenced by the 'bell-curve' distribution of total radiation (Figure 7b), and stone temperatures at 5 mm depth in the SE and SW facing samples, respectively, were around 6° and 8 °C higher than air temperatures recorded at the same time. These radiation data also indicate the reduced daylight hours during winter.

During the period of sub-zero air temperature conditions experienced in December, stone temperatures in the SW facing block remained above 0°C because of radiative heating under clear sky conditions while stone temperatures at 5 mm below the surface in the NE facing block remained below 0°C. These data highlight the significance of aspect in creating potentially favourable conditions for the operation of different weathering processes.

3.1.2 Depth-Related Temperature Fluctuations

Due to the quantity of material recorded, again only selected data from measurements recorded in July at depth (5, 10, 20, 50 and 100 mm) in the NE (Figure 8a) and SW (Figure 8b) facing blocks are reported.

During the hours of darkness, the NE and SW facing block temperatures at each depth converged to within 0.2°C of each other. During daytime solar heating depth-related temperature variations widened, with differences of up to 4°C recorded between 5 and 100 mm depth (Figure 8a, Inset 1). Not surprisingly, temperatures are more dynamic closer to the surface with temperatures at 5 mm depth exhibiting higher values and more rapid rates of change than those at greater depth (Figure 8b). For example, following a period of cloud cover and reduction of incoming direct insolation from around 17.40 hours (Figure 8b, Inset 1), temperatures at 5 and 10 mm decreased first, whereas temperature decreases at 50 and 100 mm were slower and more diffuse.

Differences occurred in the subsurface cooling response of the NE and SW facing blocks. Data from the SW facing block collected in the summer recording period (June–July) identified a ‘cross-over’ or reversal in thermal conditions between different depths within the sandstone. At dusk as the effects of direct solar radiation receipt declined the outer 5–50 mm of stone started to cool while deeper into the block the 100 mm sensor indicated that this cooling was less pronounced with the result that for several hours the thermal gradient established during the day in which temperatures decreased from the outer layers of stone block to depth was reversed. Hall *et al.* (2008a) reported the same feature, stating that it indicates that during the warming phase near surface locations heat faster than at 100 mm depth, while during the cooling phase near-surface locations lose heat more rapidly than at 100 mm depth. It is important to note that this trend was so clearly developed in the NE facing sample reflecting the naturally lower receipt of direct solar radiation and the reliance on convective heating.

3.2 Overview of Moisture Data

Resistivity sensors show that clear seasonal differences in moisture content exist for all aspects with a peak during winter months followed by a decline during spring and summer months to a minimum point in September. However, this seemingly simple long-term trend masks a much greater level of complexity in the shorter-term reflecting changing inputs (typically rainfall) and outputs (evaporation). Consequently, on a day-to-day basis within the longer-term trend, moisture content can be extremely variable.

This variability is most clearly demonstrated through the mobility of the ‘wetting front’ with its arrival identified by a rapid decrease in the Resistance Ratio (RR) indicated by the moisture sensors. The term ‘wetting front’ is used to identify the boundary between wet and dry or less wet stone. The rate of movement of the wetting front reflects both intrinsic and extrinsic factors. The former include stone properties such as porosity and pore connectivity, properties that determine the hydraulic conductivity characteristics of stone. The latter include factors such as the intensity and duration of rainfall events and input of additional energy from wind that helps to drive moisture deeper into the stone fabric than it would otherwise have done under more calm conditions.

Data collected during the monitoring period identified the presence of wetting fronts across all aspects and at all monitored depths with the exception of the 100 mm depth (Figure 9a–d). However, there are clear differences between different aspects and the depth of the wetting front with, for example, the NW facing sample exhibiting the lowest number of near-surface wetting events. Figure 9b shows that following 3 days of exposure a ‘wetting front’ was identified at a depth of 5 mm below the block surface in the NE facing sample with the RR decreasing from 1.0 to 0.25 over a period of 5 minutes in response to a rainfall event. The same ‘wetting front’ was detected at depths of 10, 20 and 50 mm after another 70, 125 and 515 minutes, respectively (Table 5).

As shown in Table 5, the progress of the wetting front differs depending on aspect and the severity of the rainfall event. For example, the rainfall hitting the NE facing block on the 12th June and 7th July takes similar times for the respective wetting fronts to reach depths of 10 and 20 mm. However, the wetting front does not reach a depth of 50 mm on the 7th July, presumably reflecting differences in the duration and intensity of the rainfall event and the amount of incident moisture.

Data indicate that the coincidence of rain, the presence of wind and high ambient humidity levels (>90%) combine to produce conditions that promote the rate of travel and penetration of the wetting front. For example, in comparison to the rainfall event of the 7th July, greater wind-speed (>14 m s^{-1}), antecedent rainfall amounts and greater duration of the rainfall event on the 12th June explain why the wetting front reached a depth of 50 mm on this date (Figure 10). Wind-driven rain is widely identified as a means of facilitating deep moisture penetration into porous material (e.g. Blocken and Carmeliet 2004; Briggen *et al*, 2009) such as the Peakmoor Sandstone used in this study. It is noted that wind impacting a porous surface can create pressure differentials of up to 3 hPa across the stone surface, conditions that encourage the inward movement of moisture (Camuffo 1995; Beall 1998; Pérez-Bella *et al*, 2013).

In addition to the wetting of stone, the resistivity sensors also recorded drying dynamics at various depths. These data clearly show that moisture cycling occurs to depths of at least 50 mm under temperate conditions and highlight the distinction between the rates at which wetting and drying processes can occur, particularly the length of time drying takes deeper into the stone and the persistence of this deeper moisture.

In general the drying of stone takes more time that the wetting of stone. For example, following the wetting of stone during the rainfall event on the 12th June, the wetting front in the NE facing sample took more than 1 hour to reach a depth of 10 mm but it took more than 200 hours for the same sensor to achieve a RR of 1.0 which is indicative of dry stone. Accepting that there may be some discrepancy between moisture conditions in close proximity to the sensor and further away from it in terms of the rate of drying, data indicate that drying is a much more energy intensive process with the same capillary forces that help draw moisture into stone and that control its subsequent movement deeper into the substrate also acting to retain moisture and prevent its evaporative loss.

Data indicate the existence of a spatial imbalance in the effectiveness of drying between the stone surface and substrate. For example, on the 12th June the NE block sensors indicated that the stone surface dried first with the sensor at 5 mm depth registering ‘dry’ conditions (RR of 1.0) after 176 hours and the sensors at 10 and 20 mm depth achieving the same condition after 201 and 366 hours, respectively. Drying, like wetting, occurs first at the stone surface and is controlled by both surface and air temperature conditions along with airflow, which facilitates evaporative loss. Consequently, surface moisture content decreases resulting in an exponential decrease in liquid hydraulic diffusivity (Hillel 1998).

This situation continues until a critical level of moisture content is reached that marks the change between capillary and vapour transport processes. At this point the moisture link between surface and substrate is disrupted with the result that the drying front recedes deeper into the stone leaving vapour diffusion as the only effective transport mechanism through which moisture held at depth can escape. As a consequence of the greater energy required to maintain the operation of this mechanism, the rate of drying slows.

Identification of the dynamics of drying are complicated by subsequent wetting events as demonstrated in Figure 11 where sensors at depths of 20 and 50 mm show increasing RR values (indicative of drying) while at the same time the sensors at 5 and 10 mm exhibit more complex fluctuations between wet and dry conditions in response to separate rainfall events on the 20th, 24th and 25th July.

In terms of stone weathering, these data highlight the greater potential for weathering activity related to the greater frequency of transitions between wet and dry conditions and hence time of wetness in the outer few millimetres of stone and support the identification by McCabe *et al*, (2015) of the development over time of within block heterogeneity where previously none existed.

4.0 Implications for Sandstone Weathering in 'Temperate' Environments

The significance of data reported here lies not so much in the actual observed values, although these are of importance in demonstrating the potential range of conditions stone in a 'temperate' environment can be exposed to, rather these temperature and moisture data provide an indication of the ever-changing and complex conditions experienced by stone over various time-scales. Frequent transitions from wet to dry and warm to cold conditions (and vice versa) and the associated energy exchanges create the potential for the operation of a variety of weathering mechanisms. These data indicate that this potential for weathering is greatest in the outer few millimetres of stone where temperature and moisture conditions are especially dynamic but they also point to the complexity of temperature and moisture cycling between the near-surface and deeper sandstone substrate.

4.1 Thermal Heterogeneity

Temperature data identified thermal responses characterised by heterogeneity with near-surface stone (c.5–10 mm) exhibiting frequent (order of minutes and probably less) but relatively low magnitude fluctuations in temperature response directly driven by environmental conditions (e.g., shade, passage of cloud, increase in wind-speed). In comparison, at the same time deeper within the stone thermal response appears to follow a much less 'energetic' regime being more closely linked to the diurnal scale of environmental heating and cooling cycles. This reflects the typically poor thermal conductivity properties of stone and the time required to transfer thermal energy received at the surface to deeper substrate areas – a response time that exceeds the duration of the near-surface short-term temperature fluctuations thereby preventing their expression.

In particular, the more 'energetic' character of heating and cooling fluctuations in the outer 5–10 mm of stone (temperature range 1–2°C) repeated day after day may contribute to the development of the physically expressed heterogeneity between surface and substrate described by McCabe *et al*, (2015) by creating conditions conducive to greater moisture flux (wetting and drying) with mobilisation and precipitation of salts and other contaminants. In addition, the ability of natural cycles of short-term (a minute or less) temperature change operating over a shallow, near-surface region to generate a sufficient shock to fracture stone has been identified by other researchers (e.g., Hall 1999; Hall and André 2001, 2003; Gómez-Heras *et al.* 2006, 2008; Smith 2009, 2012) with the critical value for this shock often cited to be a temperature change of 2 °C/minute (Richter and Simmons 1974; Yatsu 1988). The frequency of occurrence of such temperature changes has been found, through high-resolution thermal monitoring studies, to be greater than previously thought (Hall and André 2001; Gómez-Heras *et al.* 2006; McKay *et al*. 2009; Molaro and McKay 2010) and data reported here tends to support these findings in a temperate environmental setting.

Despite the debate that continues over the role of insolation-related weathering in the breakdown of stone, technological developments now allow researchers to more accurately quantify the effects of heating and cooling on stone. This is demonstrated by Collins and Stock (2016) who showed that exposure to repeated thermal cycles created cumulative deformation capable of fracturing exfoliating sheets of granite. Although they focus on a different lithology to that reported here, their work highlights the significance of repeated thermal cycling and its role in the weakening of stone.

With regard to the role of thermal response in establishing the condition of thermal heterogeneity, aspect-related differences in the nature of heating regimes (ie; the relative inputs of radiative versus convective heating) may contribute to the degree of heterogeneity that develops (Figure 12). For example, data reported here indicate that those aspects exposed to a greater amount of radiative heating exhibit more 'energetic' thermal response characteristics in the outer few millimetres of stone and it is suggested that, overtime, the rate and extent of the development of emerging heterogeneity in such aspects would be greater. This in turn may have significant implications for differences in the efficacy of weathering processes, their depth of penetration into stone and the subsequent rate of deterioration.

This thermal heterogeneity is similar to the physical heterogeneity identified by McCabe *et al*, (2015) in that it demonstrates spatially variable properties. However, whereas the emerging heterogeneity identified by McCabe *at al*, (2015) reflects the effect of spatially variable physical properties within stone such as porosity and permeability, the establishment of thermal heterogeneity is linked primarily to the effects of aspect and the resulting differences in externally derived receipt of radiative (as opposed to convective) heating during daylight hours. Consequently, thermal heterogeneity is an ephemeral characteristic breaking down during the hours of darkness when the effect of radiative heating is removed and the effect of aspect is lost as convective heat exchange dominates.

It is important to note that data reported here represent the response of 'quarry fresh' stone in which any weathering-related physical heterogeneity between surface/near-surface and deeper substrate material has not had time to develop. Consequently, we can only speculate as to whether the thermal response of aged stone would be similar or whether the physical change in the outer few millimetres of stone would result in the development, during daylight hours, of an increased or decreased thermal heterogeneity.

The 5 mm boundary identified here is determined by the location of the temperature sensors and should therefore be viewed as an indicator and not a definitive measurement of boundary position. It is probable that the boundary between the more energetic conditions in the outer few millimetres of stone and the more 'organised' and predictable conditions in the deeper substrate is transitional, changing in response to factors such as energy conditions incident at the stone surface, time of day and time of year.

4.2 Moisture Dynamics and Weathering Implications

It is widely recognised that temperature exercises a critical control on the occurrence and severity of stone decay and the efficacy of weathering processes that cause it (Hall *et al.* 2012). But temperature is not only important because of the stresses it may induce through differential heating, it also exerts an influence on, and operates in conjunction with, other factors to breakdown stone (Gómez-Heras *et al,* 2006). In particular, its impact on moisture availability and movement, including evaporative processes which are directly dependent on temperature conditions (Gómez-Heras *et al,* 2006; Turkington *et al,* 2002).

It is this impact on moisture dynamics that may have the greatest implications for weathering in temperate environments. In particular, the aspect-related differences in the observed temperature values presented here may have implications for disruption of 'hydraulic continuity' between stone surface/near-surface regions and the deeper substrate of wet stone. This situation could arise when rapid temperature cycling driving evaporative drying in the surface and near-surface zone results in a progressive reduction in surface moisture content disrupting the hydraulic pathways and hence continuity between the surface and depth resulting in the drying front receding to a subsurface position. Such disruption will then necessitate the subsequent loss of moisture from depth to occur by vapour diffusion, which is a less effective mechanism of moisture movement. In a temperate environmental setting, reduction in the effective movement of moisture from deep within stone to the surface may contribute to the establishment of a longer time of deep wetness of stone particularly during winter months when the frequency and often the intensity of moisture inputs are greater (McCabe *et al*, 2013; Shokri and Or, 2011; McAlister *et al,* 2016).

The physical effect of prolonged deep wetting of stone is not yet fully understood but through the process of ion diffusion it may initially facilitate the movement of salts and other contaminants deep into the fabric of stone where, following a sufficient accumulation, under anaerobic conditions chemical weathering through prolonged exposure to alkaline pore water may contribute to the destabilisation of silicate minerals (McCabe *et al,* 2010). While the effect of such changes to the substrate will not be immediately felt they may create weaknesses that will eventually gain surface expression as the existing stone surface weathers back. It seems reasonable to assume that any such deep-seated degradation of stone will be spatially variable reflecting differences in such factors as pore connectivity and micro-structural features, which facilitate the passage of moisture in some parts of stone and restrict it elsewhere.

Such an influence on moisture flux will by association also influence the location and kinetics of salt crystallisation within pores (Rodriguez-Navarro and Doehne 1999), given that increasing temperatures can promote the precipitation of salts, and decreasing temperatures can encourage salts to dissolve (Camuffo 1998; Smith *et al.* 2011). Moreover, upon heating, salts that have crystallised within pores typically experience volume increases greater than that of most stone-forming minerals (Goudie and Viles 1997; Smith 2012). The thermal heterogeneity described in the previous section highlights how spatially and temporally variable temperature conditions may control the depth of penetration and mobility of contaminants such as salt that are carried by moisture. Data reported here show that the SW facing block experienced the greatest number of wetting and drying cycles at depths of 5, 10, 20 and 50 mm reflecting both the greater incidence of rainfall because of the prevailing direction of weather systems and the greater potential for direct receipt of solar radiation in comparison to other aspects.

As mentioned previously, temperature plays a fundamental role in the freezing of water within pores. This occurs at varying sub-0°C temperatures (depending on, for example, pore size and water chemistry) and is thought, to act, through several mechanisms to induce stress within stone (McGreevy 1981; Hall 2007). The freezing temperature and rate of freezing (as well as stone moisture conditions) are thought to be factors that determine the activity and efficacy of particular freeze-thaw mechanisms. Aspect related differences in the establishment and persistence of sub-0°C temperatures is demonstrated by data whereby the higher stone temperatures recorded in the SW facing block negate the potential for freeze–thaw weathering effects while simultaneously, the NE facing block showed the potential for the freezing of pore moisture with sub-0°C temperatures recorded 5 mm below the block surface. However, no breakdown of stone associated with freezing events occurred during the recording period although that is not to say that freezing within the substrate did not occur but was of insufficient duration, intensity and / or extent to result in material breakdown and loss.

Finally, it is also important to acknowledge that temperature (along with moisture) exercises a critical control on stone-dwelling organisms. Stone temperature has recently been considered to comprise a significant and dynamic component of the bio-receptivity of a stone surface in the context of lichen colonisation, to the extent that an annual difference of just 3°C may be enough to determine whether a lichen can or cannot survive on a particular surface (McIlroy de la Rosa *et al.* 2013). Equally, the persistence of moisture within stone can create conditions conducive to the growth of algae on and within stone and this is an area of growing debate as to whether the observed increase in extensive algal growth on stone in temperate environments and on different aspects is related to a shift to wetter winter conditions related to climate change (Adamson *et al*, 2010, 2013).

5.0 CONCLUSION

Temperature is a key control on the operation and effectiveness of stone decay processes, acting directly to influence change or indirectly to speed or slow change through other mechanisms of decay. Under 'temperate' environmental conditions data indicate that the thermal response of stone is not simple but is made up of numerous short-term, small-scale fluctuations superimposed on the larger scale diurnal cycles of heating and cooling. While the latter are quite predictable, the former are less so and create conditions in the outer few millimetres of stone that frequently fluctuate thereby providing repeated impulses for change in the presence of moisture and contaminants such as salt.

The complexity of thermal response identified in the Peakmoor sandstone samples investigated in this study means that unravelling the various feedback interactions between components of the weathering system, so as to better understand the dynamics of stone breakdown, is fraught with difficulties. Chief amongst these is the interaction between physical heterogeneity (as expressed in porosity and permeability differences between near surface and the deeper substrate – McCabe *et al*, 2015), and thermal heterogeneity (with near surface conditions dominated by rapid short-term fluctuations while more subdued conditions dominated by diurnal heating and cooling cycles prevail in the deeper substrate).

Moisture dynamics within sandstone are equally complex with data identifying a near-surface region in which frequent moisture cycling takes place thereby creating the potential for more weathering activity. Under certain conditions, where moisture inputs exceed evaporative loss and where windspeeds are high, moisture can penetrate beyond the dynamic near-surface zone (5–10 mm) to greater depth where it may remain for lengthy periods of time particularly during winter months. Data also indicated that the subsequent drying of stone takes much longer than initial wetting because of the greater energy required to extract moisture from the stone. Consequently once moisture starts to accumulate at depth it may become increasingly difficult to remove especially when the hydraulic connection between near-surface and deeper substrate regions of stone is disrupted resulting in the subsequent loss of this deep moisture being reliant on the mechanism of vapour diffusion alone.

Despite the complexity of the moisture characteristics and their spatial and temporal variability, it is important to remember that the data reported here were gathered from a type of sandstone that has relatively homogeneous structural and mineralogical characteristics. Therefore, it seems reasonable to assume that the movement of moisture in more heterogeneous and/or weathered sandstones maybe much more complicated with structures such as clay laminations and variable pore sizes creating complex hydraulic pathways that can draw moisture deeper into stone and restrict its subsequent removal (McAllister *et al*, [In press]). Consequently, our understanding of moisture dynamics in particular requires much more detailed investigation.

Acknowledgements

The authors wish to acknowledge the contribution made to the inception of this project by the late Professor Bernard Smith. During the period of this research, Dr Daniel McAlister was in receipt of post-graduate PhD funding from the Engineering and Physical Sciences Research Council, UK (EPSRC Grant EP/G0151X/1). Finally, the authors would like to acknowledge the reviewers insightful comments, which have undoubtedly contributed to an improved final version of this paper.

References

Adamson, C.S., McCabe, S., McAllister, D., Smith, B.J. & Warke, P.A. 2010. Mapping the spatial distribution of precipitation, biological soiling and decay on monuments in Northern Ireland: towards understanding long-term stone response to moisture. *XIX Congress of the Carpathian Balkan Geological Association*, Thessaloniki, Greece, Vol. 99, 183–190.

Adamson, C.S., McCabe, S., Warke, P.A., McAllister, D. & Smith, B.J. 2013. The influence of aspect on the biological colonization of stone in Northern Ireland. *International Biodeterioration and Biodegradation*, 84, 357–366.

Beall, C. 1998. *Thermal and moisture protection manual: for architects, engineers and contractors*. London, McGraw-Hill.

Betts, N.L. 1997. Climate. In: Cruickshank, J.G. (ed.) *Soil and environment: Northern Ireland.* Belfast: Department of Agriculture for Northern Ireland and Queen's University Belfast, 63–84.

Blocken, B. & Carmeliet, J. 2004. A review of wind-driven rain research in building science. *Journal of Wind Engineering and Industrial Areodynamics*, 92, 1079–1130.

Briggen, P.M., Blocken, B.J.E. & Schellen, H.L. 2009. Wind-driven rain on the façade of a monumental tower: numerical simulation, full-scale validation and sensitivity analysis. *Building and Environment*, 44, 1675–1690.

Building research establishment (BRE) 2000. Peakmoor Sandstone: Technical Data Sheet. http://projects.bre.co.uk/ConDiv/stonelist/peakmoor.html (Accessed 18.05.16).

Camuffo, D. 1995. Physical weathering of stone. *Science of the Total Environment*, 167, 1–14.

Camuffo, D. 1998. *Microclimate for Cultural heritage*. Elsevier, Amsterdam.

Caputa, Z.A. 2016. The impact of solar radiation on the temperature of the exposed rocks of the karst canyon (the Kraków-Częstochowa Upland, Poland). *Bulletin of Geography. Physical Geography Series*, No.10: 19–30.

Collins, B.D & Stock, G.M. 2016. Rockfall triggering by cyclic thermal stressing of exfoliation fractures. *Nature Geoscience*, 9: 395–400.

Gómez-Heras, M., Smith, B.J. & Fort, R. 2006. Surface temperature differences between minerals in crystalline rocks: implications for disaggregation of granites through thermal fatigue. *Geomorphology,* 78, 236–249.

Gómez-Heras, M., Smith, B.J. & Fort, R. 2008. Influence of surface heterogeneities of building granite on its thermal response and its potential for the generation of thermoclasty. *Environmental Geology*, 56, 547–560.

Goudie, A.S. & Viles, H.A. 1997. *Salt Weathering Hazards*. Wiley, Chichester.

Gunzberger, Y. & Merrien-Soukatchoff, V. 2011. Near-surface temperatures and heat balance of bare rock outcrops exposed to solar radiation. *Earth Surface Processes and Landforms*, 36, 1577-1589.

Hall, K. 1997. Rock temperatures and implications for cold region weathering, 1: new data from Viking Valley, Alexander Island (Antarctica). *Permafrost and Periglacial Processes*, 8, 69–90.

Hall, K. 1999. The role of thermal stress fatigue in the breakdown of rock in cold regions. *Geomorphology*, 31, 47–63.

Hall, K. 2007. Monitoring of thermal conditions in building stone with particular reference to freeze-thaw events. In: Kourkoulis, S.K. (ed.) *Fracture and Failure of Natural Building Stones*. Springer, Dordrecht, 373–394.

Hall, K. & André, M-F. 2001. New insights into rock weathering from high frequency rock temperature data: an Antarctic study of weathering by thermal stress. *Geomorphology*, 41, 23–35.

Hall, K. & André, M-F. 2003. Rock thermal data at the grain scale: applicability to granular disintegration in cold environments. *Earth Surface Processes and Landforms*, 28, 823–836.

Hall, C. & Hoff, W.D. 2002. *Water Transport in Brick, Stone and Concrete*. Taylor and Francis, New York.

Hall, K., Meiklejohn, I., Sumner, P. & Arocena, J. 2010. Light penetration into Clarens Sandstone and implications for deterioration of San Rock Art. *Geoarchaeology*, 25, 122–136.

Halsey, D.P., Mitchell, D.J. & Dews, S.J. 1998. Influence of climatically induced cycles in physical weathering, *Quarterly Journal of Engineering Geology*, 31, 359–367.

Hillel, D. 1998. *Environmental Soil Physics*. Academic Press, London.

Iñigo, A.C. & Vivente-Tavera, S. 2002. Surface-inside (10 cm) thermal gradients in granitic rocks: effect of environmental conditions. *Building and Environment*, 37, 101–108.

Jenkins, K.A. & Smith, B.J. 1990. Daytime rock surface temperature variability and its implications for mechanical rock weathering in Tenerife, Canary Islands. *Catena*, 17, 449–459.

McAllister, D., McCabe, S., Srinivasan, S., Smith, B.J. & Warke, P.A. 2011. Moisture dynamics in building sandstone: implications for the transport and accumulation of salts. In: Ioannou, I & Theodoridou, M. (eds) *Salt Weathering on Buildings and Stone Sculptures*, SWBSS 2011. Limassol, Cyprus, 39–46.

McAllister, D., McCabe, S., Smith, B.J., Srinivasan, S., & Warke, P.A. 2013. Low temperature conditions in building sandstone: the role of extreme events in temperate environments. *European Journal of Environmental and Civil Engineering*, 17, 99–112.

McAllister, D., Warke, P.A., McCabe, S. & Gomez-Heras, M. 2016. Evaporative moisture loss from heterogeneous stone: material-environment interactions during drying. *Geomorphology* 273, 308–322.

McCabe, S., Smith, B.J. and Warke, P.A. 2007a. Preliminary observations on the impact of complex stress histories on sandstone response to salt weathering: laboratory simulations of process combinations. *Environmental Geology*, 52, 251-258.

McCabe, S., Smith, B.J. & Warke, P.A. 2010. Exploitation of inherited weaknesses in fire-damaged sandstone: the 'fatiguing' of 'shocked' stone. *Engineering Geology*, 115, 217–225.

McCabe, S., Brimblecombe, P., Smith, B.J., McAllister, D., Srinivasan, S. & Basheer, P.A.M. 2013. The use and meanings of 'time of wetness' in understanding building stone decay. *Quarterly Journal of Engineering Geology and Hydrogeology*, 46, 469–476.

McCabe, S., McAllister, D., Warke, P.A. & Gomez-Heras, M. 2015. Building sandstone surface modification by biofilm and iron precipitation: emerging block-scale heterogeneity and system response. *Earth Surface Processes and Landforms*, 40(1), 112–122.

McFadden, L.D., Eppes, M.C., Gillespie, A.R. & Hallet, B. 2005. Physical weathering in arid landscapes due to diurnal variation in the direction of solar heating. *Geological Society of America Bulletin*, 117 (1/2), 161–173.

McGreevy, J.P. 1981. Some perspectives on frost shattering. *Progress in Physical Geography*, 5, 56–75.

McGreevy, J.P. & Whalley, W.B. 1987. Progress report: weathering. *Progress in Physical Geography*, 11, 357–369.

McIlroy de la Rosa, J.P., Casares Procel, M. & Warke, P.A. 2013. Mapping stone surface temperature fluctuations: implications for lichen distribution and biomodification on historic stone surfaces. *Journal of Cultural Heritage*, 14, 346–353.

McKay, C.P., Molaro, J.P. & Marinova, M.M. 2009. High frequency rock temperature data from hyper-arid desert environments in the Atacama and the Antarctic Dry Valleys and implications for rock weathering. *Geomorphology*, 110, 182–187.

Molaro, J.P. & McKay, C.P. 2010. Processes controlling rapid surface temperature variations on rock surfaces. *Earth Surface Processes and Landforms,* 35, 501–507.

Pel, L. & Huinink, H. 2009. NMR imaging of moisture and ion transport in building materials. In: Codd, S.L. & Seymour, J.D. (eds) *Magnetic Resonance Microscopy*, Wiley-VCH, Weinheim, 451–464.

Pérez-Bella, J.M., Dominguez-Hermándezz, J., Rodriquez-Soria, B., del Coz-Diaz, J.J. & Cano-Sunen, E. 2013. Combined use of wind-driven rain and wind pressure to define water penetration risk into building facades: the Spanish case. *Building and Environment*, 64, 46–56.

Richter, D. & Simmons, G. 1974. Thermal expansion behavior on igneous rocks. *International Journal of Rock Mechanics and Mining Science and Geomechanics Abstracts,* 11, 403–411.

Rodriguez-Navarro, C. & Doehne, E. 1999. Salt weathering: influence of evaporation rate, supersaturation and crystallization pattern. *Earth Surface Processes and Landforms*, 24, 191–209.

Sass, O. 2003. Moisture distribution in rockwalls derived from 2D-resistivity measurements. *Zeitschrift für Geomorphologie, Suppl. Bd*., 132, 51–69.

Sass, O. 2005. Rock moisture measurements: techniques, results, and implications for weathering. *Earth Surface Processes & Landforms* 30: 359-347.

Sass, O. & Viles, H.A. 2010a. Wetting and drying of masonry walls: 2D-resistivity monitoring of driving rain experiments on historic stonework in Oxford, UK. *Journal of Applied Geophysics*, 70, 72–83.

Sass, O. & Viles, H.A. 2010b. 2D resistivity surveys of the moisture content of historic limestone walls in Oxford, UK: implications for understanding catastrophic stone deterioration. In: Smith, B.J., Gómez-Heras, M., Viles, H.A. & Cassar, J. (eds) *Limestone in the Built Environment: Present Day Challenges for the Preservation of the Past*. Geological

Society of London Special Publication 331, 237–249.

Shokri, N. & Or, D. 2011. What determines drying rates at the onset of diffusion controlled stage-2 evaporation from porous media? *Water Resources Research*, 47, W09513, doi:10.1029/2010WR010284.

Smith, B.J. 1977. Rock temperature measurements from the northwest Sahara and their implications for weathering. *Catena,* 41, 41–63.

Smith, B.J. 2009. Weathering processes and forms. In: Parsons, A.J. & Abrahams, A.D. (eds) *Geomorphology of Desert Environments* (2nd edition), Springer, 69–100.

Smith, B.J. 2012. Weathering. In: Holden, J. (ed) *An Introduction to Physical Geography and the Environment*, Pearson, Essex, 185-214.

Smith, B.J., Srinivasan, S., Gómez-Heras, M., Basheer, P.A.M. & Viles, H.A. 2008. Experimental studies of near-surface temperature and moisture cycling and surface wetting of stone and its implications for salt weathering. In: Ottosen, L.M., Rrig-Dalgaard, I., Larsen, P.K., Brajer, I., Bøllingstoft, P., Marciniak, M. and Svane, M. (eds) *Proceedings from the International Conference of Salt Weathering on Buildings and Stone Sculptures*, Copenhagen, October 2008, 65-77.

Smith, B.J., Srinivasan, S., Gómez-Heras, M., Basheer, P.A.M. & Viles, H.A. 2011. Near-surface temperature cycling of stone and its implications for the scales of surface deterioration. *Geomorphology*, 130, 76-82.

Srinivasan, S., Basheer, P.A.M., Smith, B.J., Gómez-Heras, M., Grattan, K.T.V. & Sun, T. 2010. Use of fiber-optic and electrical resistance sensors for monitoring moisture movement in building stone subjected to simulated climatic conditions. *Journal of ASTM International,* 7, January 2010.

Stojanovič, G., Radovanovič, M., Malesev, M. & Radonjanin, V. 2010. Monitoring water content in building materials using a wireless passive sensor. *Sensors*, 10, 4270–4280.

Turkington, A.V., Smith, B.J. & Basheer, P.A.M. 2002. The effect of block retreat on subsurface temperature and moisture conditions in sandstone. In: Prikryl, R. & Viles, H.A. (eds) *Understanding and Managing Stone Decay*. Karolinum Press, Prague, 116–126.

Viles, H.A. 2005. Microclimate and weathering in the central Namib Desert, Namibia. *Geomorphology,* 67, 189-209

Warke, P.A. 2000. Micro-environmental conditions and rock weathering in hot, arid regions. *Zeitschrift für Geomorphologie Supplement,* 120, 83–95.

Warke, P.A. and Smith, B.J. 1994. Short-term rock temperature fluctuations under simulated hot desert conditions: some preliminary data. In: Robinson, D.A. & Williams, R.B.G. (eds) *Rock Weathering and Landform Evolution*. Wiley, Chichester, 57-70.

Yatsu, E. 1088. *The Nature of Weathering: An Introduction*. Sozosha, Tokyo.

LIST OF TABLE CAPTIONS

Table 1: Examples of investigations of stone temperatures in the natural environment.

Table 2: Summary of structural and mineralogical properties of Peakmoor Sandstone.

Table 3: Average winter and summer values based on Met Office data collected over 30 years from 1981–2010.

Table 4a: Summary of air temperature and subsurface stone temperature conditions at 5, 10, 20, 50 and 100 mm depths during the June–July recording period.

Table 4b: Summary of air temperature and subsurface stone temperature conditions at 5, 10, 20, 50 and 100 mm depths during the October–December recording period.

Table 5: Data showing rate of movement of wetting front in relation to rainfall events. These data should be read in conjunction with the graphs in Figure 9 where the numbered rainfall events are identified as 1, 2, 3, and 4.

Table 1

Author(s)	Location	Material	Recording Frequency	Depth of Measurement from Surface (mm)
Smith (1977)	Morocco; Tunisia	Limestone	20 min	50, 100
Hall (1997)	Antarctica	Sandstone	1, 2 min	0, 5, 10, 15, 30, 50
Halsey et al, (1998)	United Kingdom	Quartz Arenite	15 min	25
Warke & Smith (1998)	USA	Sandstone, Granite, Marble, Limestone	1 min	0, 25
Hall & André (2001)	Antarctica	Granodiorite	1 min	0
Inigo & Vicente-Tavera (2002)	Spain	Granite	4 hr	10
Viles (2005)	Namibia	Marble, Granite	3 hr, 1 min	0
McKay et al, (2009)	Chile, Antarctica	Dolerite	1 s	0
Hall et al (2010)	South Africa	Sandstone	2 min	0, 0.5, 1
Molaro & McKay (2010)	USA	Dolerite, Sandstone	0.375 s	0
Gunzburger & Merrien-Soukatchoff (2011)	France	Gneiss	1 hr	<10, 100, 200, 300, 400, 500
Caputa (2016)	Poland	Limestone	1 hr ?	0, 50

Table 2:

Property	Value	Comment / Data Source
Age	Carboniferous (360–300 Ma)	Part of the Millstone Grit Group
Primary Mineralogy	Quartz	Illite and kaolinite are present as diagenetic clay phases
Apparent Density	2264.50 kg/m^3	Original measurement
Porosity accessible to H_2O	16.46 %	BRE 2000
Porosity accessible to Hg	16.37 %	Original measurement
Mean Pore Diameter	0.31 µm	Original measurement
Average Air Permeability	31.67 mD	McCabe et al, 2007
Saturation Coefficient	0.68	BRE 2000
Water Absorption Capacity	5.07 %	BRE 2000

Table 3:

Location	Month	Max. Temp (°C)	Min. Temp (°C)	Frost Days	Rainfall (mm)	Rain Days >1mm
Belfast	January	7.9	2.2	7.5	90.4	14.7
	July	19.7	11.7	0.0	66.0	12.1

Table 4a

	Block Temperatures (°C) – June–July				
Sensor Depth From Surface	**Northeast Facing**	**Southeast Facing**	**Southwest Facing**	**Northwest Facing**	**Air Temperature**
5 mm					
Mean	16.3	16.3	16.4	16.0	11.4
Maximum	26.7	31.2	34.6	29.5	23.5
Minimum	6.0	5.8	6.1	5.9	5.9
Range	20.7	25.5	28.5	23.5	17.6
10 mm					
Mean	16.2	16.3	16.4	16.0	11.4
Maximum	26.6	31.2	34.3	29.2	23.5
Minimum	5.9	5.7	6.1	6.0	5.9
Range	20.7	25.8	28.2	23.2	17.6
20 mm					
Mean	16.3	16.3	16.3	15.9	11.4
Maximum	26.6	31.2	33.9	29.1	23.5
Minimum	6.0	5.7	6.0	5.9	5.9
Range	20.6	25.4	27.9	23.2	17.6
50 mm					
Mean	16.2	16.3	16.3	15.9	11.4
Maximum	26.5	30.4	33.1	28.4	23.5
Minimum	6.1	5.9	6.1	6.1	5.9
Range	20.3	24.4	26.9	22.4	17.6
100 mm					
Mean	16.1	16.1	16.2	15.8	11.4
Maximum	26.3	29.1	31.9	27.5	23.5
Minimum	6.4	5.9	6.1	6.0	5.9
Range	20.0	23.2	25.8	21.4	17.6

Table 4b

	Block Temperatures (°C) – October–December				
Sensor Depth From Surface	**Northeast Facing**	**Southeast Facing**	**Southwest Facing**	**Northwest Facing**	**Air Temperature**
5 mm					
Mean	7.4	7.9	7.7	7.1	8.0
Maximum	17.0	21.9	23.0	17.9	17.0
Minimum	-2.5	-2.4	-2.4	-2.5	-0.3
Range	19.5	24.4	25.5	20.3	17.3
10 mm					
Mean	7.4	7.9	7.6	7.2	8.0
Maximum	17.0	21.9	22.9	17.9	17.0
Minimum	-2.5	-2.5	-2.5	-2.4	-0.3
Range	19.5	25.0	25.4	20.2	17.3
20 mm					
Mean	7.4	7.8	17.6	7.1	8.0
Maximum	17.0	21.9	22.5	17.7	17.0
Minimum	-2.5	-2.5	-2.4	-2.5	-0.3
Range	19.5	24.4	24.9	20.2	17.3
50 mm					
Mean	7.3	7.9	7.6	7.2	8.0
Maximum	16.7	20.7	21.9	17.5	17.0
Minimum	-2.6	-2.3	-2.5	-2.5	-0.3
Range	19.3	23.0	24.3	20.0	17.3
100 mm					
Mean	7.5	7.7	7.6	7.1	8.0
Maximum	16.8	19.6	20.9	17.0	17.0
Minimum	-2.4	-2.5	-2.4	-2.5	-0.3
Range	19.3	22.0	23.3	19.5	17.3

Table 5

Block Aspect	Date of Detection at 5 mm	Rainfall Total & Duration	Time of arrival of wetting front in minutes following detection at 5 mm				
			5 mm	10 mm	20 mm	50 mm	100 mm
(1) North-west	17.07.2011	4.2 mm over previous 2 days	Datum point	5	135	755	–
(2) North-east	12.06.2011	7.6 mm over previous 2 days	Datum point	70	125	515	–
(3) North-east	07.07.2011	1.4 mm in preceding 15 hours	Datum point	75	125	–	–
(4) South-east	17.06.2011	2.8 mm in preceding 10 hours	Datum point	60	85	520	–

FIGURES

Figure 1: Porosity characteristics of Peakmoor Sandstone derived from Mercury Intrusion Porosimetry (MIP) analysis.

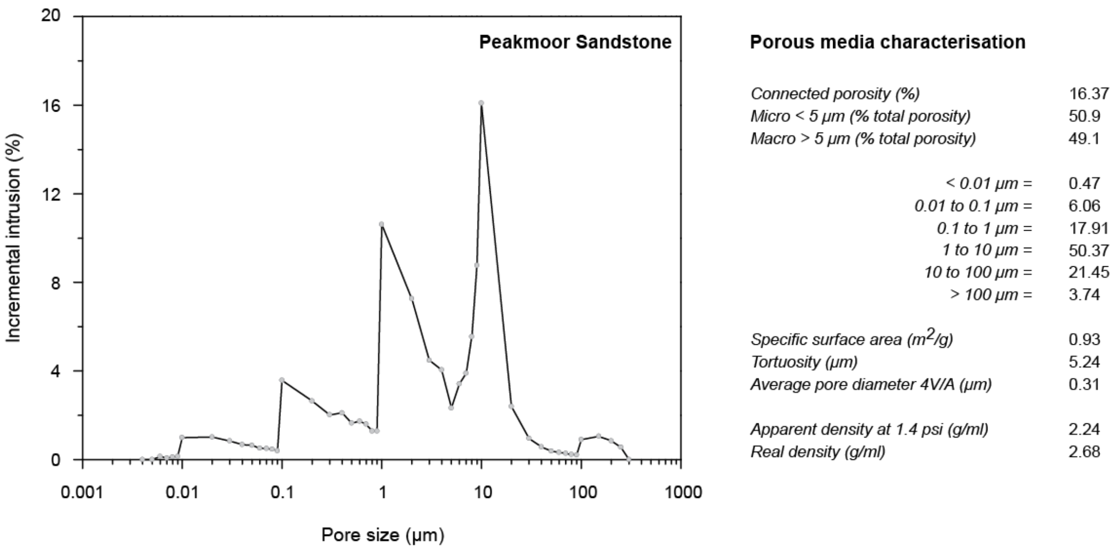

Figure 2: Location of field exposure site.

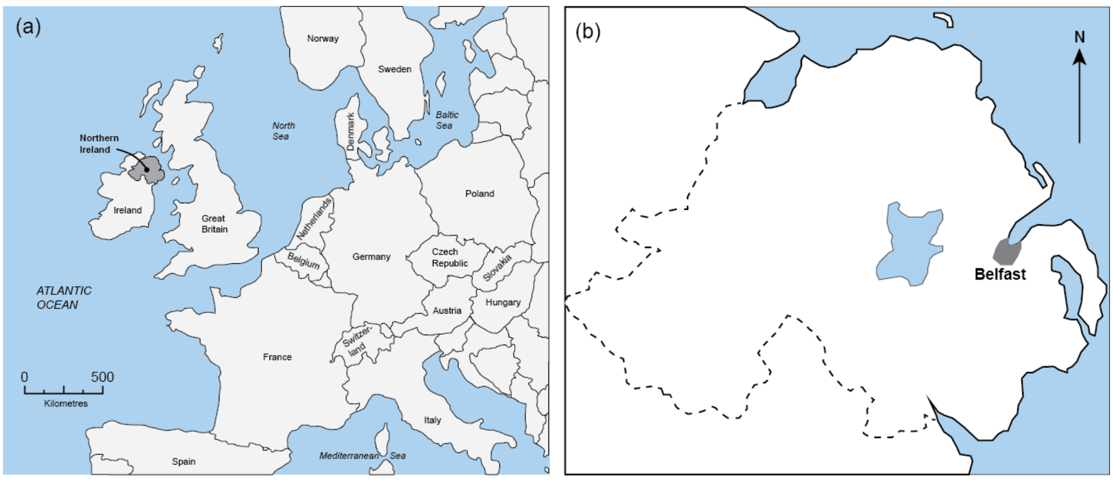

Figure 3: Experimental test unit with Peakmoor Sandstone samples in situ.

Figure 4: Diagram of test blocks showing: **a)** positioning and depth of the embedded temperature and moisture sensors (rear view); **b)** how each drilled sensor cavity was sealed (side view); c) position of sensors in cross-section.

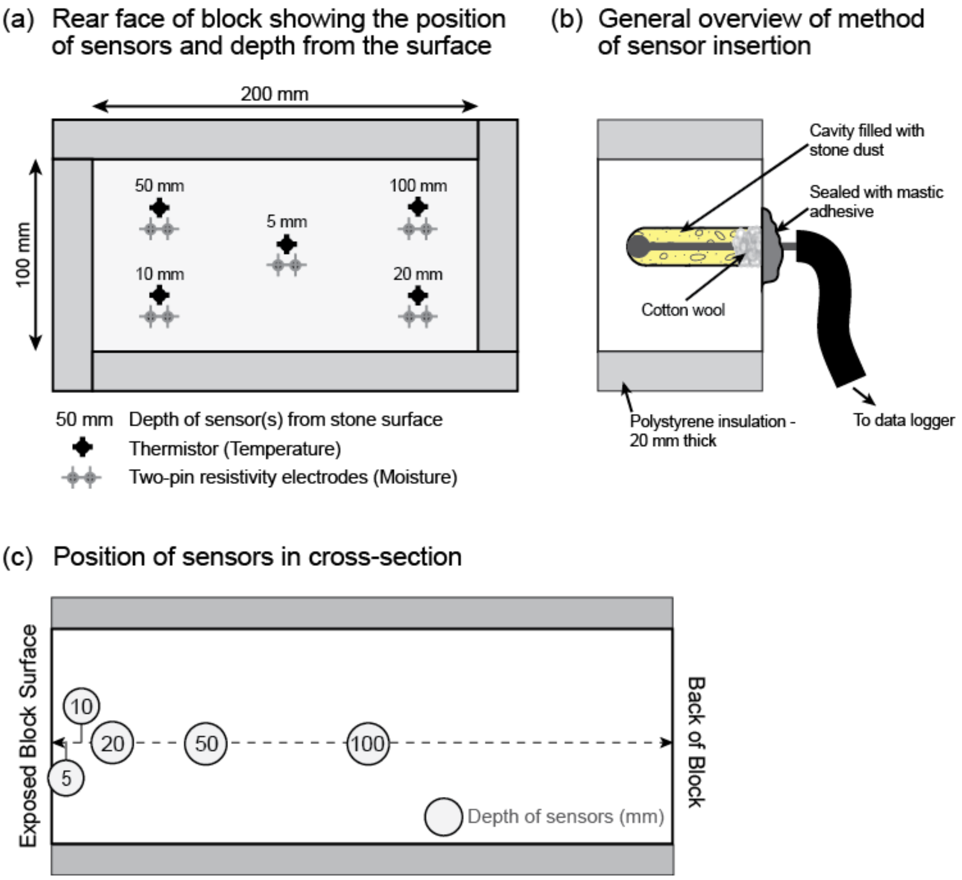

Figure 5a: Temperature data from 5, 10, 20, 50 and 100 mm below the surface of the northeast (NE) and southwest (SW) facing blocks collected during the June–July recording period.

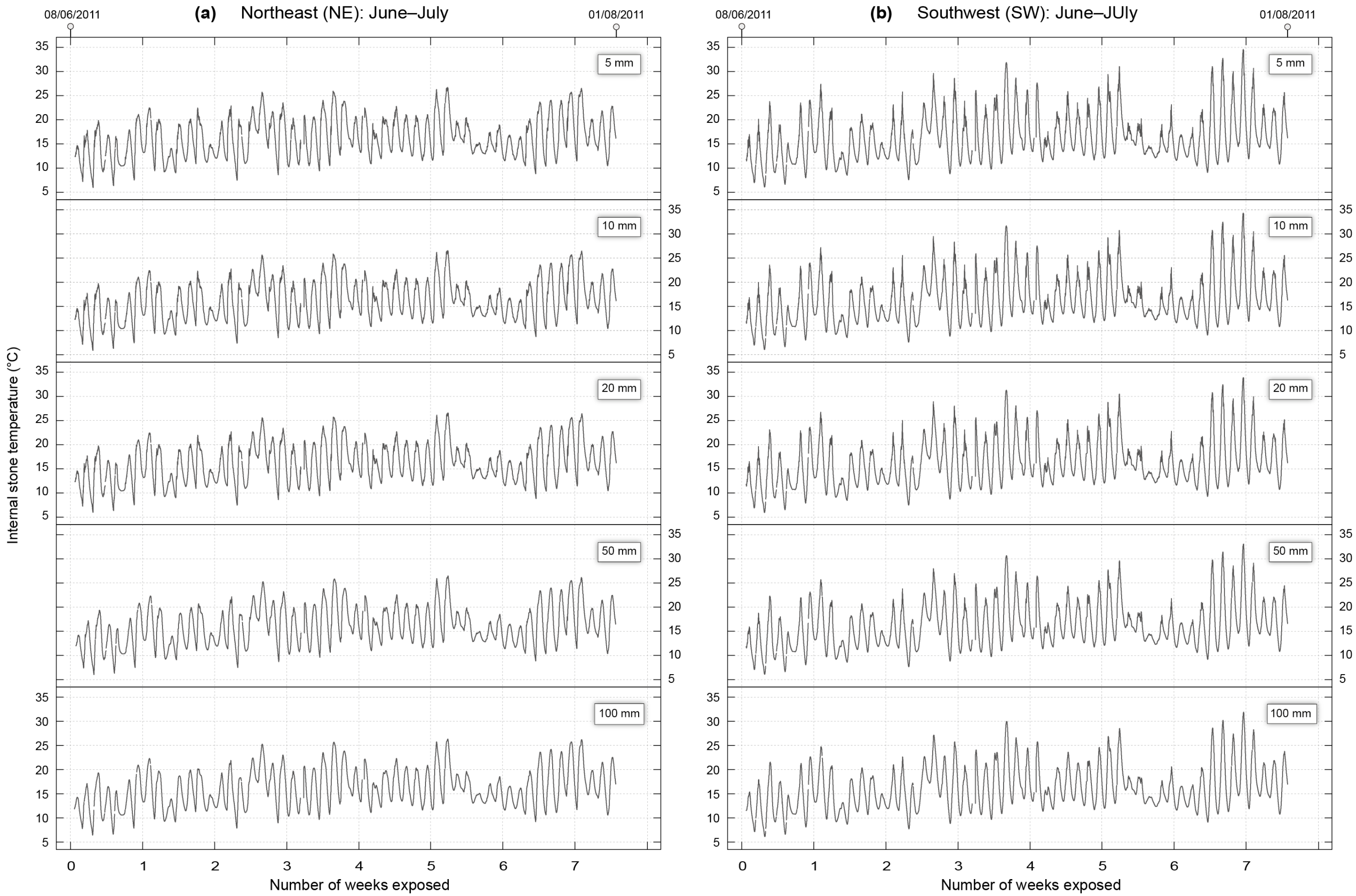

Figure 5b: Temperature data from 5, 10, 20, 50 and 100 mm below the surface of the northeast (NE) and southwest (SW) facing blocks collected during the October–December recording period

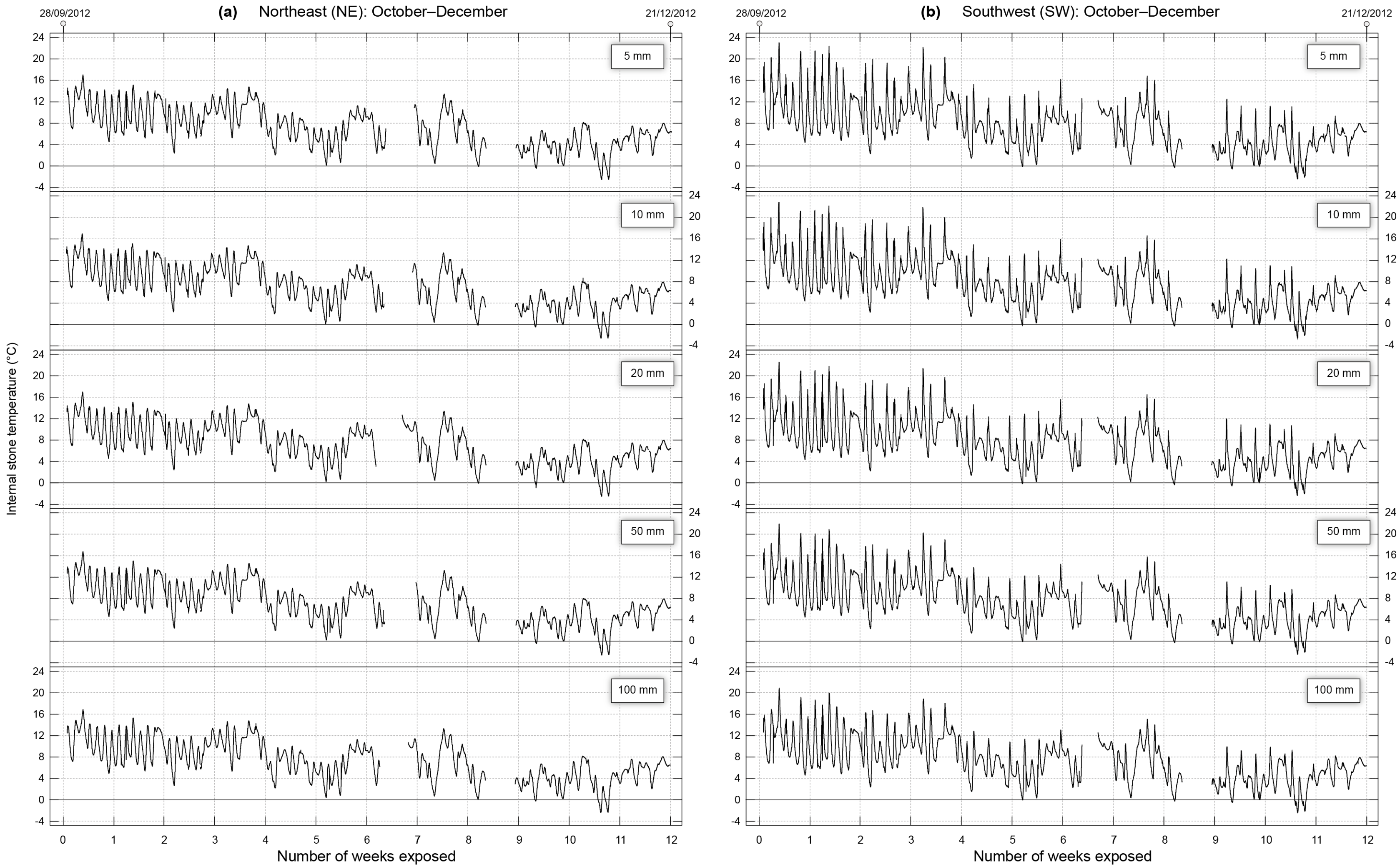

Figure 6: Air temperature conditions and internal stone temperatures (5 mm depth) according to aspect during: a) overcast conditions; and, b) clear sky conditions - data were collected in the near-surface structure during the June-July monitoring at 5-minute intervals; it is important to note the different temperature scale in the temperature data presented in the insets.

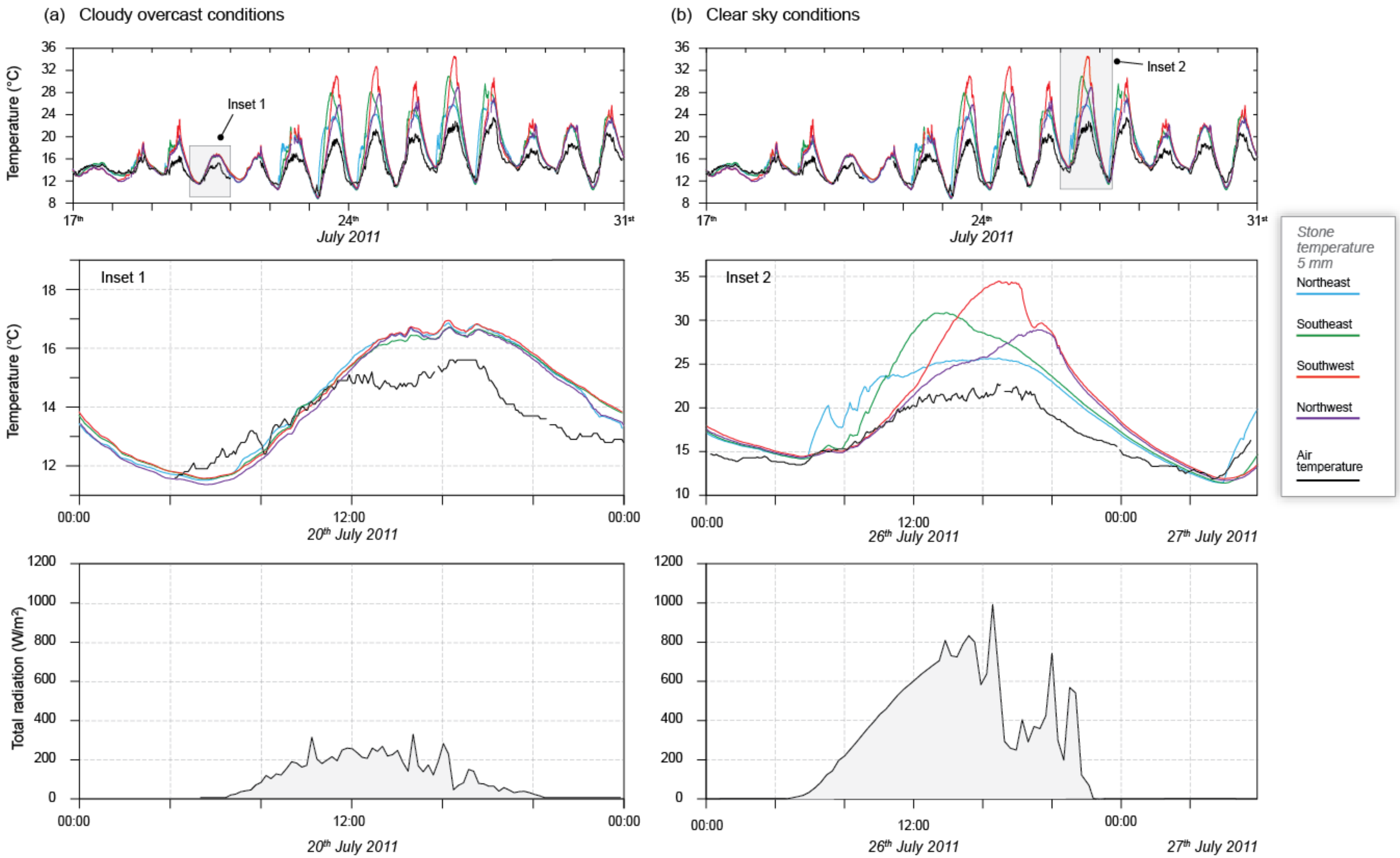

Figure 7: (a) Three day series of temperature data recorded 5 mm below the block surfaces from all exposure aspects; (b) total solar radiation recorded over the same period.

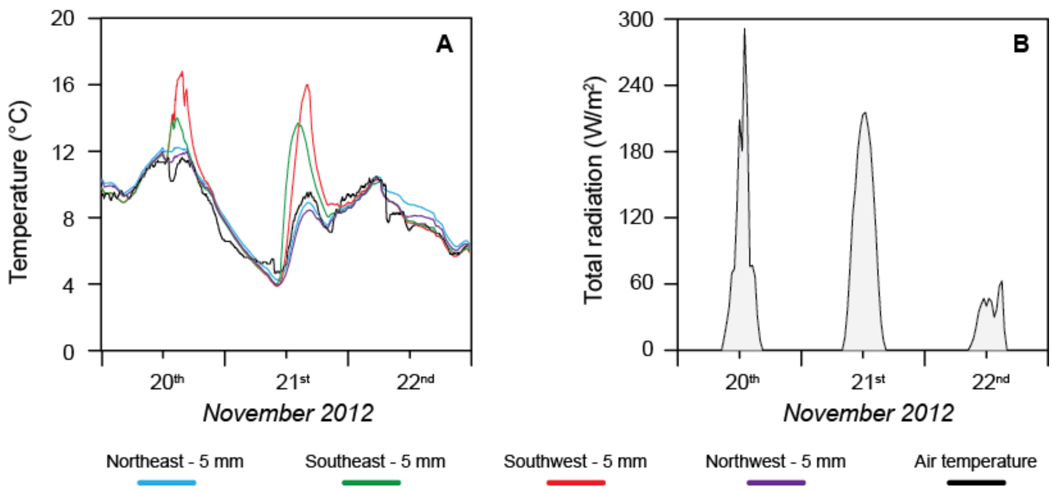

Figure 8: Depth-related temperature differences recorded in (a) the northeast facing block and, (b) the southwest-facing block with selected detail from both datasets shown in the relevant insets.

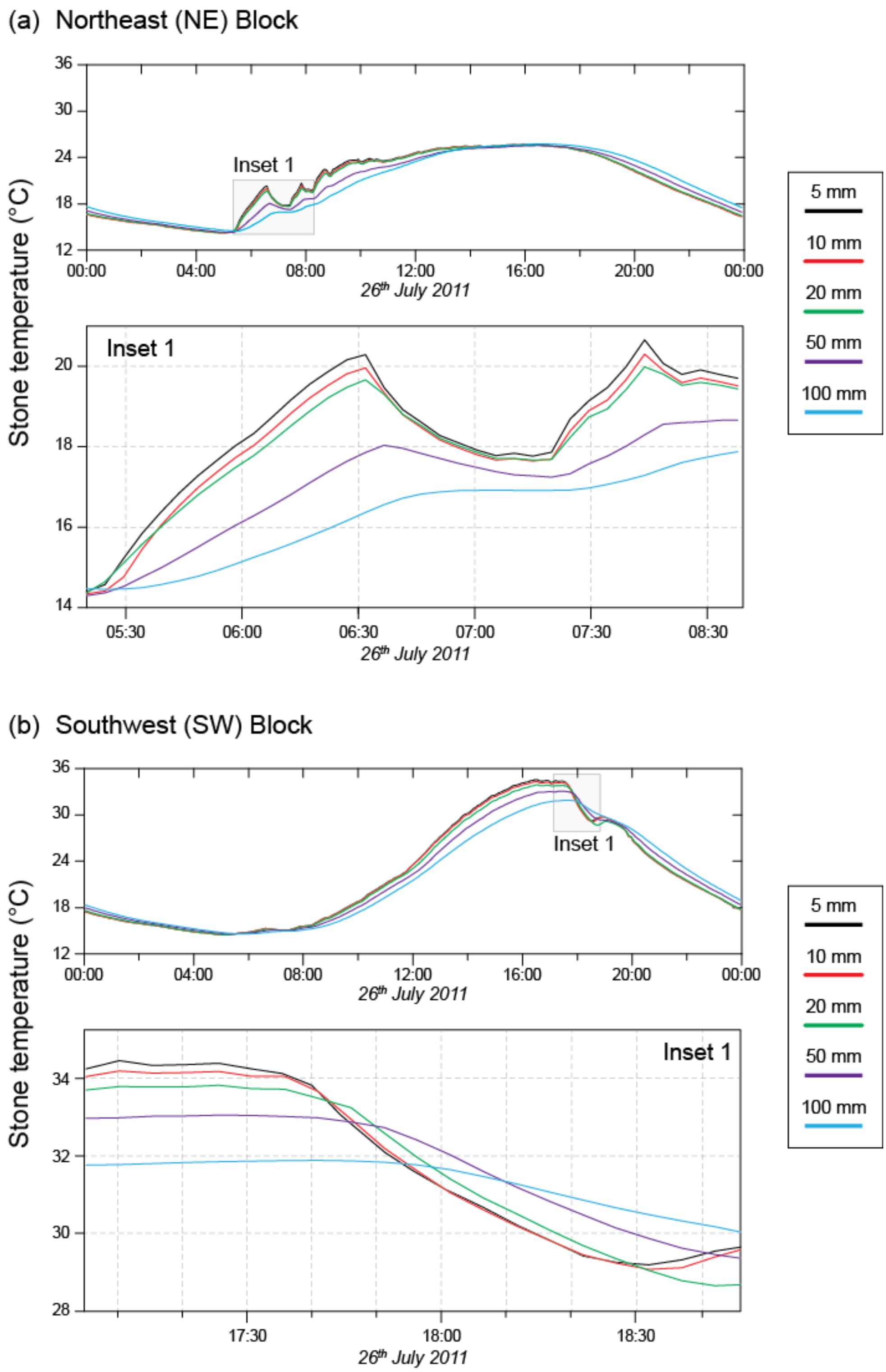

Figure 9: Development of wetting fronts in all Peakmoor Sandstone samples identified during the June–July recording period. Unfortunately data from the sensor located at 5 mm below the surface of the southwest facing block is missing because of technical problems with the sensor.

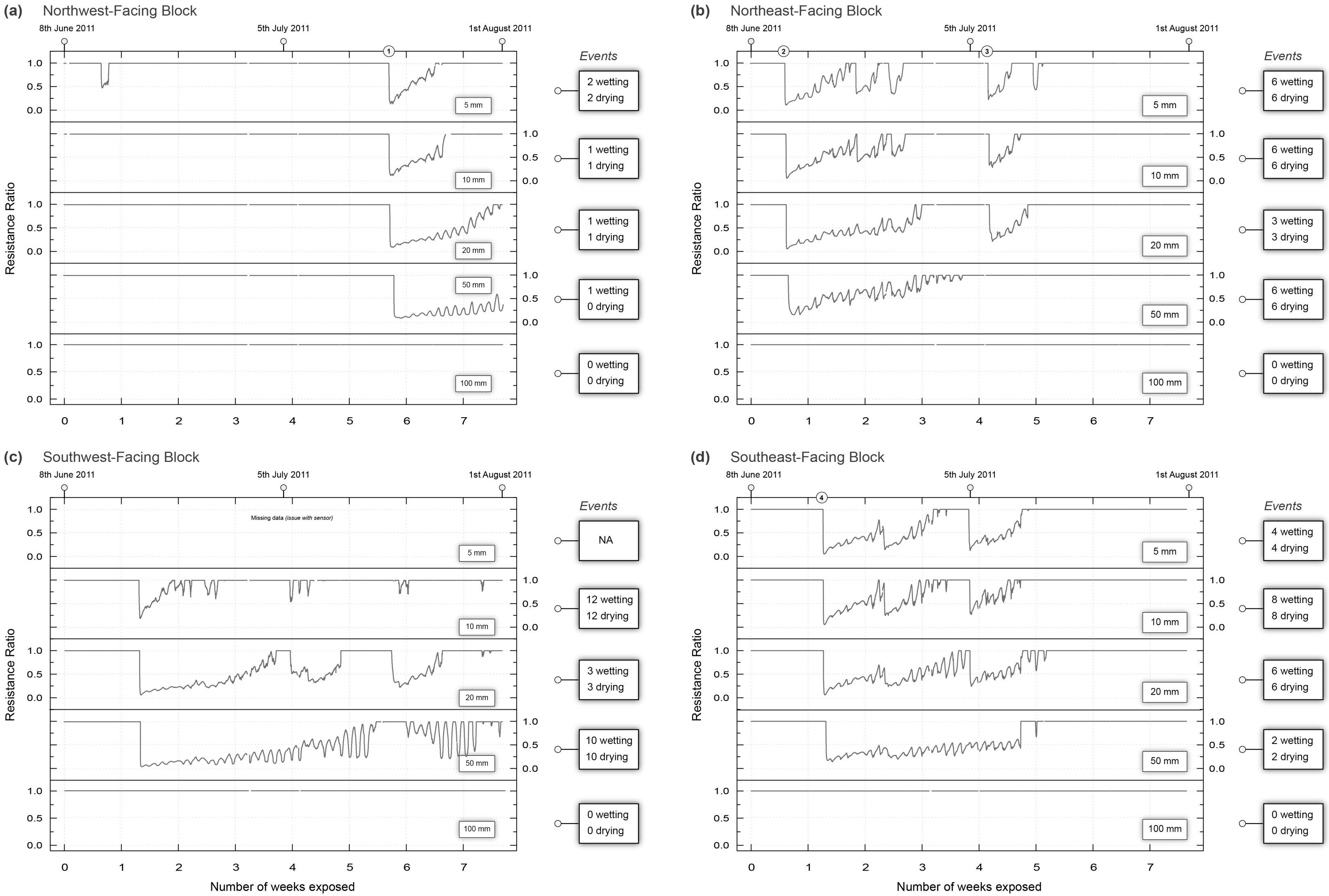

Figure 10: Arrival of wetting front (light grey shaded vertical line) at 5 mm depth in northeast-facing sample and links with the prevailing meteorological conditions. (a & b) resistivity data and rainfall totals on 10–12 June and 7 July; (c & d) windspeed, air temperature and relative humidity on 10–12 June; (e & f) windspeed, air temperature and relative humidity on 7 July.

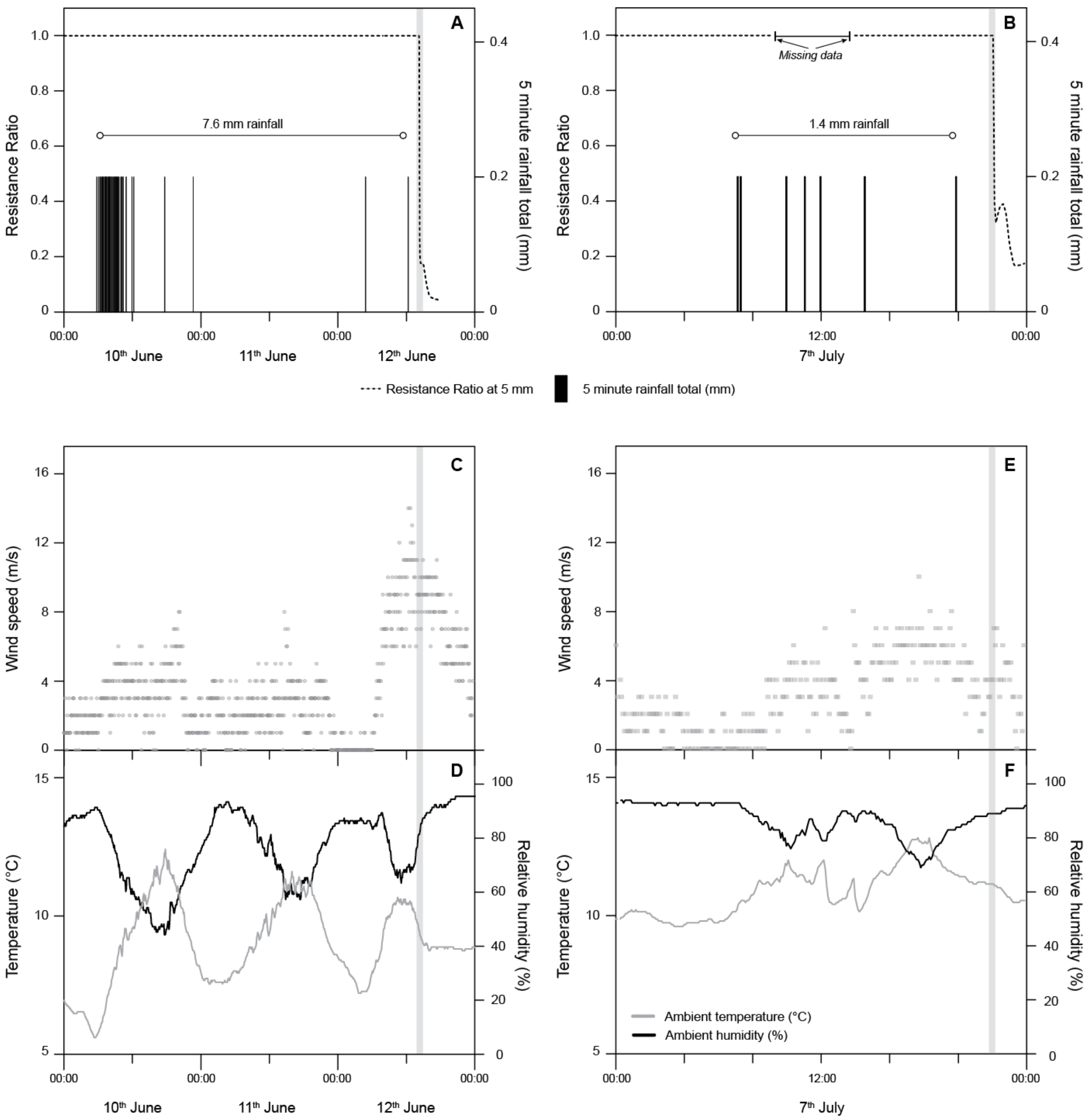

Figure 11: Detail of the drying sequence as recorded at depths of 5, 10, 20 and 50 mm below the surface of the northeast-facing block following a rainfall event. The relative 'time of wetness' is also shown as a percentage of the 17-day period.

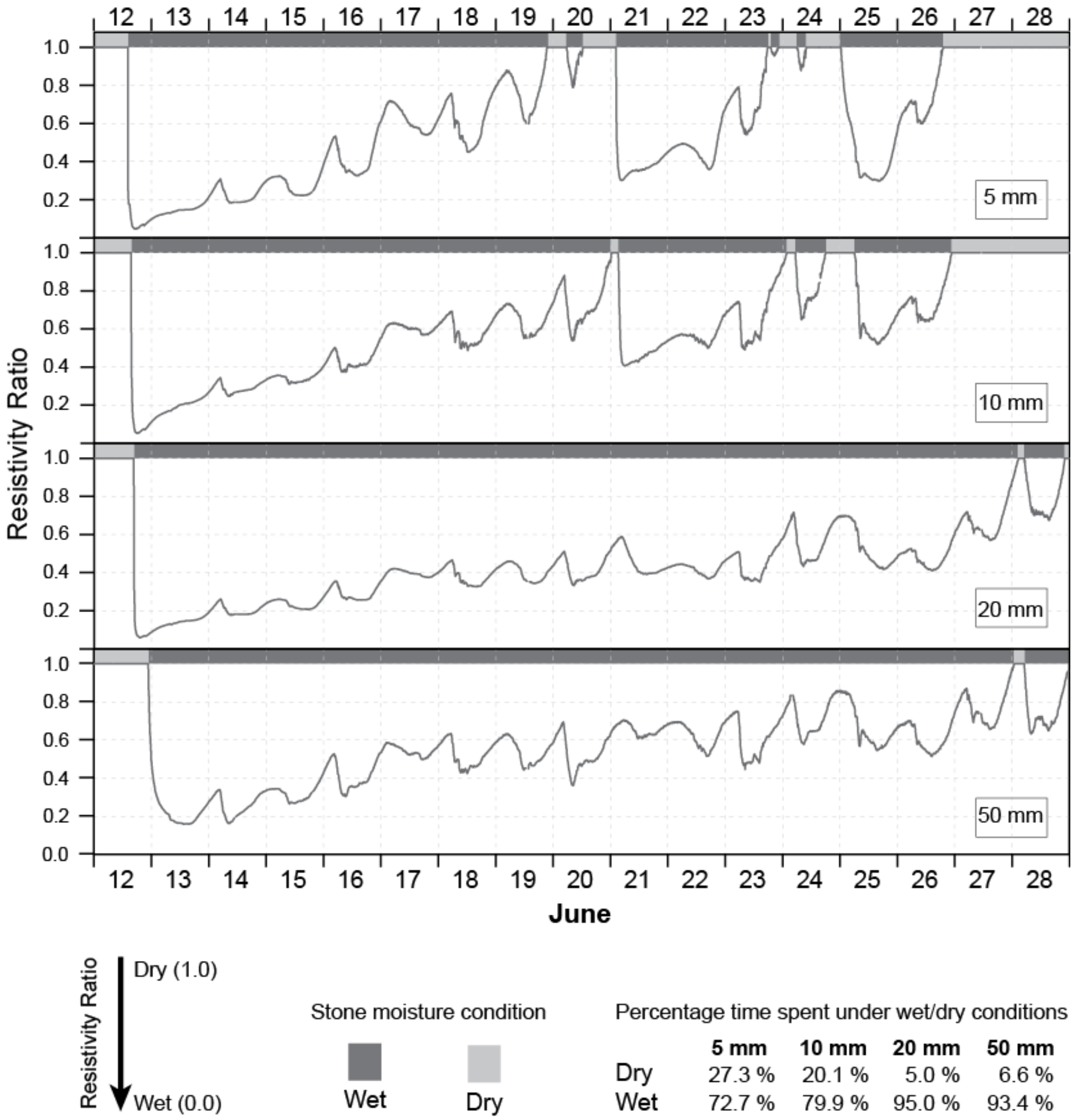

Figure 12: Conceptual model of the development of differences in thermal response characteristics between stone exposed to different aspects and between the near-surface and deeper fabric of stone.